

## Tone Production in Mandarin-speaking Children with Cochlear Implants: A Preliminary Study

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**Objective**—More than a quarter of the world's population speak tone languages, such as Mandarin Chinese. In those languages, the pitch or tone pattern of a monosyllabic word conveys lexical meaning. The purpose of this study was to investigate tone production in Mandarin-speaking children with cochlear implants (CIs).

**Material and Methods**—Speech samples were recorded from seven normal-hearing and four CI children aged 4–9 years. All subjects were native Mandarin speakers. The speech samples were used for acoustic analysis of the tone patterns, i.e. the fundamental frequency contours. In addition, a tone intelligibility test was carried out in which four normal-hearing native Mandarin-speaking adults listened to the speech materials and judged the intelligibility of the children's tone production.

**Results**—The tone production for the seven normal-hearing children was considered to be perfect in the intelligibility test. Acoustic analysis of the speech materials of the normal-hearing children produced the four typical tone patterns of Mandarin Chinese: (i) high and flat; (ii) rising; (iii) low and dipping; and (iv) falling. The tone patterns produced by the children with CIs tended to be flat, with some other patterns being irregular. The results of the tone intelligibility tests also showed degraded intelligibility of tone patterns.

**Conclusion**—A potential speech development deficit was documented in prelingually deafened children with CIs whose native language is a tone language. The imperfect tone production of the implant children, which can be attributed to the paucity of pitch information delivered via the current CI stimulation, may have significant implications for communication using tone languages. Further research is warranted to determine factors that may affect tone development in children with CIs. *Key words:* cochlear prosthesis, pitch, tone language.

### INTRODUCTION

Contemporary multichannel cochlear implants (CIs) have provided benefit to thousands of patients with profound hearing loss throughout the world. The number of implant recipients in China and Southeast Asia has increased dramatically in recent years. At Beijing Tongren Hospital alone, the total number of cochlear implantees has reached 350 since the CI program was started only 8 years ago. The number of new implantees is expected to be  $\approx 140$  per year, 90% of whom will be children.

In China and Southeast Asia, tone languages are most prevalent. These include Mandarin Chinese, Cantonese, Vietnamese, Thai, etc. In these tone languages, the tone pattern (or simply tone), as defined by the fundamental frequency (F0) of the voiced part of a syllable, varies. In Mandarin Chinese, a language spoken by more people than any other, there are four tone patterns. The pitch contours of tones 1–4 are (i) flat and high, (ii) rising, (iii) low and dipping and (iv) falling, respectively. The unique characteristic of the tone language is that the variations of the tone patterns of each syllable convey lexical meaning. For instance, tones 1–4, when associated with the Chinese syllable /qi/ (pronounced “chee”), can mean (i) “seven”, (ii) “flag”, (iii) “get up” and (iv) “air”, respectively.

Given the current understanding of electrical hearing and pitch coding, pitch information of complex acoustic stimuli, such as speech and music, is unlikely to be strong and is probably lacking in contemporary CI systems [for a review, see Moore (1)]. Sporadic reports concerning a limited number of native Chinese-speaking patients have shown that the tone recognition performances of these patients vary tremendously, ranging from chance performance to  $\approx 80\%$  correct (2–5). Two recent studies on tone recognition in Cantonese children with CIs have shown that they perform just slightly above chance levels, suggesting that children with CIs have great difficulty in extracting the pitch information needed to identify the lexical tones (6, 7).

Auditory input is essential for normal speech and language development. How do children with CIs develop tone production under conditions of impoverished auditory inputs? This study was designed to explore tone development in children with CIs whose native language is Mandarin Chinese.

### MATERIAL AND METHODS

Four prelingually deafened children (S1–S4; age range 4.0–8.75 years) in whom hearing loss had been identified at birth and who received Nucleus 24M CIs at Beijing Tongren Hospital participated in the

Table I. Demographic information for the four CI subjects

Subject No.	Age (years)	Sex	Etiology of deafness	Age at activation (years)	Duration of CI use (years)	Speech-processing strategy
S1	8.75	F	Unknown	3.75	5.0	SPEAK
S2	5.91	F	Unknown	3.58	2.33	ACE
S3	5.91	F	Ototoxicity	3.83	2.08	ACE
S4	4.0	F	Congenital	3.0	1.0	SPEAK

study. Demographic information for the subjects is shown in Table I. As controls, seven normal-hearing children (N1–N7; age range 3.0 and 8.5 years) were also recruited. All subjects were from native Mandarin-speaking families, with Mandarin Chinese being the only language used.

Speech samples from both normal-hearing children and children with CIs were recorded in a sound-treated room. Speech was elicited by asking the subjects to count from 1 to 10 in Mandarin Chinese. Imitated speech was also elicited by asking the children to repeat after an adult native Mandarin speaker the 4 tone patterns of the 10 sets of Mandarin syllables (/fu/, /ji/, /ma/, /qi/, /shi/, /wan/, /xi/, /yan/, /yang/ and /yi/) that have all 4 tone patterns. This resulted in 40 speech samples (4 tone patterns  $\times$  10 syllables). The speech materials were stored on tape and then transferred to the hard disk of a computer with a sampling rate of 22 050 Hz in a 16-bit format.

Acoustic analysis of the speech materials focused on the extraction of F0s, i.e. the tone patterns. The 40 imitated speech samples were subjected to F0 extraction. For 1 of the CI subjects, S4, the speech sample obtained by counting from 1 to 10 was used instead, because it was not possible to elicit imitated speech from her. First, the consonant part of the syllables was removed from the speech sample using a sound processing program (CoolEdit 2000; Syntrium Software, Scottsdale, AZ). Next, the F0s were extracted from the vowel part of the syllables using an autocorrelation method (8) in MATLAB (MathWorks, Natick, MA). Finally, a post-processing procedure was undertaken to fix any errors in F0 measured with the autocorrelation method, as F0 doubling or halving did occur. In this procedure, the F0s obtained with the autocorrelation analysis were plotted over the narrow-band spectrograms. Corrections were necessary when the F0 plotted was not consistent with the F0 shown on the spectrograms.

In addition to the acoustic analysis of the F0s of the speech materials, a tone-pattern intelligibility test was performed by four normal-hearing native Mandarin-speaking adult subjects. These adult subjects listened to the imitated speech and the speech of counting and then provided a subjective score for the intelligibility

of the tone patterns for each of the child subjects. The scores were integers between 0 and 10, with 0 being “no tonality at all” and 10 being a “perfect” score.

## RESULTS

Examples of the spectrograms of the four tone patterns of the vowel part of the Chinese syllable /qi/ are shown in Fig. 1. The upper and lower panels represent speech data recorded from a normal-hearing subject (N7) and a child with a CI (S3), respectively. The F0s extracted by means of the autocorrelation analysis are plotted as white dotted lines on the spectrograms, confirming the accuracy of the F0 measurements. The tone patterns can be seen from the contours of the F0s and more clearly from the contours of the higher harmonics. The F0s for the normal-hearing child showed the typical flat and high (tone 1), rising (tone 2), low and dipping (tone 3) and falling (tone 4) contours. It is noteworthy that tone 3 in our sample of normal-hearing children tended to show the low and dipping rather than the falling and then rising contours that we commonly saw in adults. In either case, tone 3 was readily perceived. The CI child’s production of tone 4 was similar to that of the normal subjects but tones 1–3 were essentially indistinguishable.

Tone production in children with CIs showed great individual differences. Fig. 2 plots the F0 contours of tones 1–4 in one of the normal-hearing subjects (N7) and all four children with CIs (S1–S4). Each line shows a tone contour for the vowel part of one of the Mandarin syllables. As stated previously, 10 syllables were recorded for each tone pattern for all the subjects except for S4, whose speech data were obtained only by counting from 1 to 10 in Mandarin Chinese. Of the Chinese words for 1 to 10, 4 are in tone 1, 1 in tone 2, 2 in tone 3, and 3 in tone 4. The tone contours in the upper group of panels are plotted using the actual time of speech production; therefore, the duration of the pronunciation of the vowels and the rate of change of a particular tone pattern can be seen from these plots. On the other hand, when the duration of the vowels was normalized to the mean duration of all vowels (318 ms in our sample), the plot of tone contours allowed easy comparison between different subjects and between different tones (Fig. 2, lower panels).

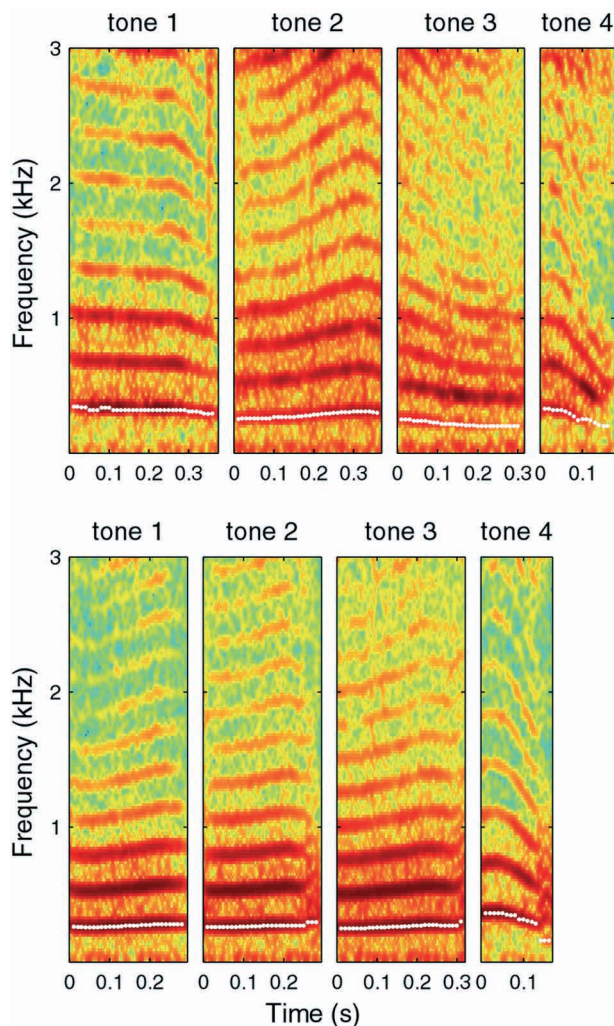


Fig. 1. Spectrograms of speech recordings from a normal-hearing child (N7; upper panels) and a child with a CI (S3; lower panels). Only the vowel parts are plotted in the spectrograms, in which red or dark red colors represent the energy associated with time (abscissa) and frequency (ordinate). The F0s extracted by means of autocorrelation analysis are plotted using white dotted lines.

The tone patterns of the normal-hearing subject showed the typical flat and high (tone 1), rising (tone 2), low or low and dipping (tone 3) and falling (tone 4) contours for all the syllables. The CI children made various errors in tone production. S1 was the best performer, her tone contours being nearly identical to those of a normal-hearing subject. For tone 3, she tended to use “glottal stops” rather than low and dipping contours, which is considered normal (9). S2 made a lot more tone-production errors than S1. Most of these errors consisted of an inability to produce a rising tone 2. Also, the F0 patterns for tone 3 varied among syllables and tended to be greatly prolonged, reflecting an added effort in producing this tone pattern. S3 produced rapidly falling tone patterns for

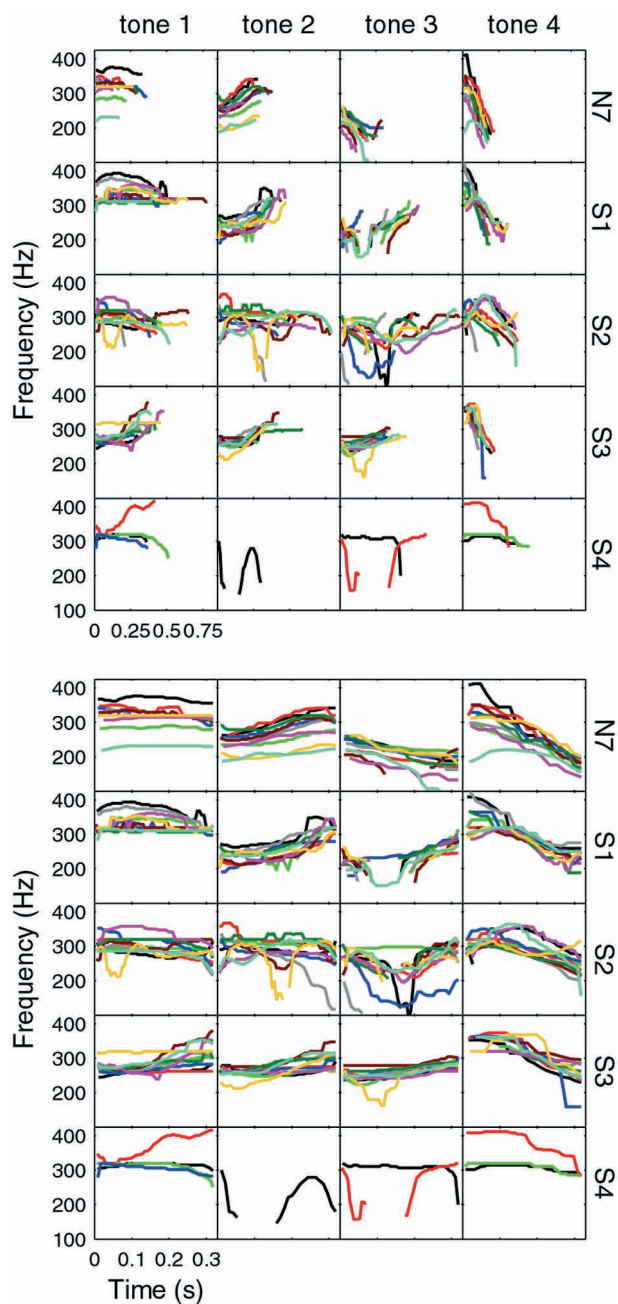


Fig. 2. Tone patterns produced by a normal-hearing child (N7) and the four children with CIs (S1–S4). Each line represents the F0 of the vowel part of a Mandarin syllable produced by a subject. The upper group of panels show the F0 contours of the original durations. The lower group of panels show the F0 contours using a normalized duration that is the mean duration of the vowel parts of all recordings (318 ms).

tone 4 (Fig. 2, upper panels). Except for one of the syllables, her tones 1–3 were all monotonic, showing a flat or sometimes slightly rising pattern (Figs. 1 and 2). Producing the falling tone pattern of tone 4 appeared to be easiest for the children with CIs. Despite all kinds of errors seen in S1–S3, their production of tone

4 was quite similar to that of the normal-hearing subjects. S4, however, demonstrated great difficulty in producing all tone patterns, including that for tone 4.

The subjective scores for the tone-pattern intelligibility test are shown in Fig. 3. All seven normal-hearing subjects received perfect scores for the intelligibility of their tone production. Therefore, only one bar is shown in Fig. 3 to represent the whole group of normal-hearing children. The mean subjective intelligibility scores for the four CI children ranged from 0.25 to 8.5. The differences in intelligibility scores between the normal-hearing children and the CI children and the differences in the scores among the CI children were found to be statistically significant ( $p < 0.05$ ; ANOVA). The variability of the scores provided by the four normal-hearing adult judges was small, as shown by the error bars (SDs) and the scatter of the original data.

## DISCUSSION

CI has provided significant benefit in terms of both receptive and expressive language skills for hearing-impaired children. It has been demonstrated in a number of studies that speech produced by English-speaking children with multichannel CIs is usually more accurate than that produced by children with comparable hearing loss but without CIs (10–14). The auditory feedback provided by the CIs is the critical

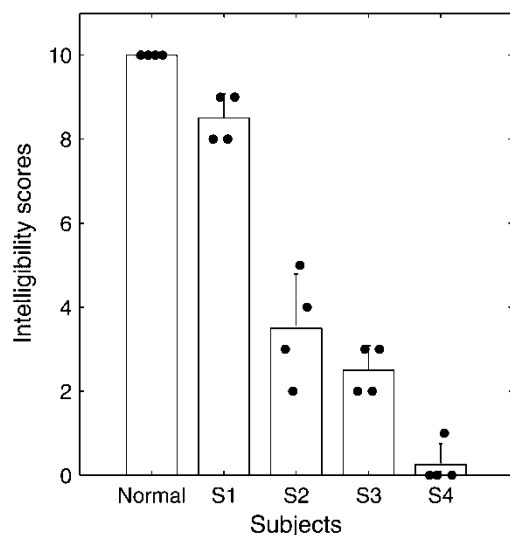


Fig. 3. Subjective intelligibility scores. The bars show the means and SDs of the intelligibility scores given by four normal-hearing adult subjects after listening to the speech materials from the normal-hearing and CI children. As all seven normal-hearing children received perfect scores for the intelligibility of their tone production, only one bar is plotted to represent the whole group of normal-hearing children. The dots show the individual scores given by the four adult judges.

factor attributed to the unprecedented achievement in language skills of hearing-impaired children.

Tone production in children with CIs was not studied in the previous research. Tone production is particularly important for native tone-language speakers, because the pitch of a syllable conveys lexical meaning. In the present study we evaluated tone production in a small group of native Mandarin-speaking children with CIs. All CI children showed imperfect tone production, making their speech intelligibility scores lower than those of the normal controls. Such a deficit in tone development is probably due to inadequate pitch information delivered via the CI stimulation. Contemporary speech-processing strategies for CIs generally have a limited number of frequency bands. Therefore, the F0 and higher harmonics cannot be resolved for pitch perception. Whereas the fine structure information within each band can potentially be useful for pitch perception (15), current speech-processing strategies emphasize the temporal envelope information and discard the fine structure information. We have shown (16) that tone perception using only the temporal envelope information in the acoustic signals is only moderately good. The question is whether such weak pitch information will be sufficient to sustain normal tone production development in children. The preliminary data from the present study suggest that it is not.

Our data also showed enormous individual differences in tone production in the children with CIs. Many factors may have contributed to those differences. Factors that affect English speech production skills in children should be considered. Tobey et al. (13) found that English speech production performance in children with CIs is influenced by non-verbal intelligence, gender, implant characteristics and educational programs. Although not found to be major contributors to English speech production performance in that study, other factors, such as age of onset of deafness, hearing aid usage, duration of deafness, age of implantation and speech-processing strategy used in the CI system, should also be considered in future studies of tone production development in children with CIs. Our preliminary data from the present study cannot resolve any of those factors due to the small number of subjects involved but hopefully will open a new area of research.

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